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SUBJECT: A Recommended Photon Production Spectrum for Thermal Neutron Capture in Chlorine

ABSTRACT

A prototype library that improved on the ENDF/B photon production data for thermal neutron capture was developed for the MSL Project and the ACTI CRADA. The data for the majority of the nuclides on this library were updated using a compilation of photon spectra from thermal neutron capture reactions by Orphan et al. Additionally, data for the Cr and Ni isotopes were updated using information contained in the Evaluated Nuclear Structure Data File (ENSDF). Both of these methods showed differences when compared with later compilations of thermal photon production data such as Lone et al. and with some experimental papers. The purpose of this research note is to compare photon production data for thermal neutron capture in Chlorine from a variety of sources (ENDF, Orphan, Lone, experimental measurements) and to generate a recommended photon production spectrum for use in future evaluations. This effort resulted in a recommended photon production spectrum containing 482 discrete gamma-rays, and pointed out serious deficiencies in the original ENDF evaluation and the two compilations by Orphan and Lone.

I. Introduction

The purpose of the Multispectral Logging Project[1–3] was to adapt nuclear well-logging techniques to map environmental contaminants along boreholes. It became apparent during this project that the neutron-induced photon-production data used by the transport codes were inadequate for this type of application. A preliminary library, containing revised photon-production data for incident thermal neutron energies, was provided by T-2 in the fall of 1994 for 21 nuclides; Cl, V, $^{50,52-54}$Cr, $^{54,56-58}$Fe, ^{55}Mn, ^{59}Co, $^{58,60-62,64}$Ni, ^{63,65}Cu, Cd, and Hg. The individual data files in this library were prepared by using a compilation of photon spectra from thermal neutron capture reactions by Orphan et al.[4] The spectrum for each nuclide from Orphan was substituted for the standard photon production spectrum for the (n,γ) reaction over all incident neutron energies for the oldest evaluations such as for Cl, or over a smaller incident neutron energy range for the newer evaluations such as 0.0-1.0 keV for the Cr isotopes. Additionally, adjustments in the Q-value for the (n,γ) reaction were also made to some of the standard evaluations. As Orphan gave the photon-production spectrum by element, the same spectrum was used for each isotope of an element, such as for the Cr isotopes.

In FY96 a closely related project was funded, the ACTI CRADA: Computer Simulation in Support of Nuclear-Well Logging.[5] One of the major tasks of the ACTI CRADA is to improve the nuclear data used by the transport codes. Of particular interest to this community is the quality of neutron-induced photon production data in the transport libraries for all incident neutron energies. As a first step, a few errors in the preliminary library from the MSL project were corrected.[6] Additionally, a new method for determining the photon production spectrum at thermal neutron energies was used for the Cr and Ni isotopes. This new method calculated the photon production spectrum from the information contained in the Evaluated Nuclear Structure Data File (ENSDF)[7] for each individual isotope.

A comparison of the photon production spectra for natural Cr and Ni showed significant differences between the two methods, Orphan and ENSDF. Additionally, comparison of the photon production spectra from Orphan or ENSDF with a more recent compilation by Lone et al.[8] indicated large differences as well. As a result of these discrepancies, it was decided that comparison to published experimental data for natural Cl and the Cr isotopes would be performed. The comparison of the photon production spectrum for natural Cl from Orphan and Lone to experimental data would give an indication of the validity of these two compilations. The comparison of the ENSDF data for the Cr isotopes to experimental measurements would give an indication of the validity of this new approach. Additionally, the calculated spectrum for natural Cr could be compared with Orphan and Lone as well for further information on these compilations. This research note documents the results of the comparison of thermal neutron photon production data for Cl. Photon production for higher energy Cl reactions is currently being addressed by T-2.

In the present work, nine sources of data were analyzed and compared to each other. Six of the sources represent the most recent experimental data that could be found. Three of the sources are older data compilations that are still currently being used. They were included to assess their value as continued sources of photon production data.

The nine data sets were compared in a two step approach. First, a simple assessment focused on 20 of the strongest gamma-rays to determine the level of agreement between each data set. This approach revealed good agreement between the majority of the sources, with the two oldest compilations in strong disagreement with the others. In the second step, the sources consistent with each other were evaluated carefully over the entire γ-ray energy range. Based on these comparisons, a recommended photon production spectrum at incident thermal energies was made for Cl.

Throughout this research note, the phrases "photon production data" and "photon spectrum" will refer to the spectrum of gamma-rays produced by capture of thermal-energy neutrons. The terms "gamma-ray", "gamma line", or simply "line" will be used to refer to any single gamma-ray in a set of photon production data. Finally, the symbol "Cl" will always refer to *natural* Cl.

Section II of this research note discusses each source of photon production data. Section III explains how the data sets were compared and how the recommended spectrum was determined. Section IV presents the recommended spectrum itself, and Section V summarizes the results of this work.

II. Description of the Data

The first task in this analysis was to gather experimental data for Cl. First, an extensive search of the internet was performed, including use of LANL's SciSearch. The "Recent References" sections of all volumes of Nuclear Data Sheets from the present back to 1978 were then searched. The cumulative subject index of Atomic Data and Nuclear Data Tables was also searched, as was the bibliographic compilation CINDA95. Finally, the references in each paper found were searched for other appropriate papers.

It should be noted at this point that ^{35}Cl completely dominates the photon production spectrum of natural Cl at incident thermal neutron energies. Natural Cl contains 75.8% ^{35}Cl and 24.2% ^{37}Cl. The thermal neutron capture cross section (σ_c^{th}) of ^{35}Cl is about 43.6 barns, but only about 0.4 barns for ^{37}Cl.

The fractional contribution of the i^{th} isotope to the total photon spectrum of Cl can be calculated from the expression

$$fractional\ \ contribution = \frac{A_i(\sigma_c^{th})_i}{\sum_j A_j(\sigma_c^{th})_j}, \tag{1}$$

where A_i is the atom fraction of the i^{th} isotope, σ_c^{th} is the radiative capture (c) cross section at thermal (th) energies, and the sum in the denominator is over the number of stable isotopes of Cl.

Using Equation 1 one finds that ^{35}Cl produces 99.72% of the photon spectrum of Cl, while ^{37}Cl only produces 0.28% at thermal energies. Because of this fact, many ^{35}Cl(n,γ)^{36}Cl experiments simply use natural Cl targets and attribute all γ-rays to ^{35}Cl. The sum of the fractional contribution of each isotope times its Q-value also equals the Q-value of the natural Cl(n,γ) reaction.

Of the initial set of around twenty-five relevant papers found, seven contained enough useful information to be included in this analysis. The most recent useful paper on ^{37}Cl was published in 1973 by Spits et al.[9] Since so much information on Cl and ^{35}Cl existed, it was decided not to include Cl or ^{35}Cl papers published before 1976. The exceptions to this rule are the two oldest sources mentioned in the introduction, Orphan[4] and ENDF/B-VI[10]. Table 1 lists information for each source of data, including the authors of the paper or evaluation, the designation that will be used to refer to the data set, and the year the data were published. Also listed is the Q-value of the reaction (if given) that the authors measured and/or used to normalize the total gamma yield. Each of these sources will now be briefly discussed.

Table 1: Listing of the data sources analyzed.

Authors	Designation	Number of γ-Rays	Year	Q-value (MeV)	Target Used
V. J. Orphan et al.[4]	Orphan[a]	144	1970	8.5765[b]	Cl
M. S. Allen and M. K. Drake[10]	ENDF/B-VI[a]	31	1967	7.9761[c]	Cl
M. A. Lone et al.[8]	Lone[a]	449	1981	—	Cl
M. L. Stelts and R. E. Chrien[11]	Stelts	76	1978	8.57975[d]	Cl
T. J. Kennett et al.[12]	Kennett	234	1981	8.57982[d]	Cl
A. M. J. Spits and J. Kopecky[13]	Spits1	420	1976	8.57939[d]	Cl
C. Coceva et al.[14]	Coceva	24	1996	—	Cl
B. Krusche et al.[15]	Krusche	400	1982	8.57968[d]	Cl[e]
A. M. J. Spits and J. A. Akkermans[9]	Spits2	79	1973	6.1077[f]	^{37}Cl

[a]These are compilations of experimental data. All others are experimental papers.

[b]Abundance and cross-section weighted value for natural Cl (see Equation 1).

[c]Abundance weighted value for natural Cl ($Q = \sum_i Q_i A_i$).

[d]Value is for ^{35}Cl(n,γ)^{36}Cl.

[e]Contributions from ^{37}Cl were subtracted from the measured spectrum.

[f]Value is for ^{37}Cl(n,γ)^{38}Cl.

Orphan: (1970)

The data set designated as Orphan[4] was taken from a compendium of thermal neutron capture gamma-rays in 75 natural elements. Published in a 1970 Gulf General Atomic report, the data were taken at the MIT Thermal Capture Gamma-Ray Facility with a Ge(Li)-NaI spectrometer. The authors state that the spectral data were corrected for the spectrometer response, and that the gamma yields were normalized to ensure that the total radiated energy per capture equaled the abundance and cross-section weighted neutron separation energy (S_n) for Cl. This weighted S_n is just the sum of the neutron separation energies for ^{35}Cl and ^{37}Cl, each multiplied by its percent contribution to the Cl photon spectrum. Normalizing the total γ-yield to the neutron separation energy (the Q-value of the capture reaction) is a common practice to improve the accuracy of the measured γ-ray intensities. It is performed by setting the total radiated energy equal to the Q-value:

$$\sum_i E_i I_i = 100Q, \qquad (2)$$

where E_i is the energy of the i^{th} γ-ray, I_i is the number of photons per 100 captures of the i^{th} γ-ray, and the sum is over all observed γ-rays. The factor required to balance Equation 2 is determined and the intensities of each γ-ray are normalized by that factor. If most transitions have been observed, this helps offset any systematic errors in the intensity measurements. Before this normalization the Orphan yield accounted for only 76.96% of the total Q-value of the Cl(n,γ) reaction.

ENDF/B-VI: (1967)

The data set designated as ENDF/B-VI[10] was taken from the sixth version of the ENDF/B data library. The actual data were obtained from the T-2 website at the URL "http://t2.lanl.gov/data/data/ENDF-VI/Cl/nat" (file 12, MT=102). This Evaluated Nuclear Data File dates back to 1967, and contains an apparent typographical error. One of the γ-rays listed has an energy of 79 keV and an intensity of 20.17 photons per 100 captures. No other source of data lists a γ-ray near that energy. Since the intensity of this line is close to the intensity resulting from the 786/788 keV doublet observed in most of the other data sources, this is most likely a typographical error.

Lone: (1981)

The data source designated as Lone[8] was taken from a 1981 catalog of prompt γ-rays from thermal-neutron capture in natural elements. It is an evaluation based on experimental data published between 1968 and March 1980, and lists Orphan, Spits1, and Stelts as references for Cl. The authors state that the γ-ray energies are weighted averages of the references' energies, while the γ-ray intensities are unweighted averages of the references' intensities. Only γ-rays with relative intensities greater than 0.05% were included.

Stelts: (1978)

The paper designated as Stelts[11] measured the γ-ray spectrum of Cl following thermal neutron capture at the Brookhaven High Flux Beam Reactor. The neutrons were moderated by bismuth crystals, and NaCl-melamine and CCl_4 targets were used. Since the neutron source was a reactor, the incident neutrons had a Maxwellian energy distribution. The γ-ray spectrum was measured with a three-crystal Ge(Li)-NaI pair spectrometer, which was calibrated relative to the $^{14}N(n,\gamma)^{15}N$ spectrum measured by Greenwood and Helmer.[16] The sum of the intensities of the 6111 keV, 6620 keV, 6628 keV, 7414 keV and 8679 keV lines were then normalized to the sum of the same line intensities measured by Spits1. The same normalization factor was used to normalize the remaining γ-ray intensities. Only γ-rays above 3.5 MeV were measured, and no attempt was made to determine a decay scheme. The authors only list "strong" γ-rays, but give no specific intensity cutoff.

Kennett: (1981)

The experiments by Kennett et al.[12] were performed at the tangential irradiation facility of the McMaster University Nuclear Reactor. A pair spectrometer was used to measure 234 lines from the $^{35}Cl(n,\gamma)^{36}Cl$ reaction. Only γ-rays with energies above 1.6 MeV were measured, and twelve of the transitions listed by Spits1 were not observed in this experiment. The detectors were calibrated relative to the $^{14}N(n,\gamma)^{15}N$ spectrum, which was measured previously by the same authors. Melamine ($C_3H_6N_6$) targets were used to measure the ^{15}N spectrum, while NH_4Cl targets were used to measure the Cl spectrum. The decay scheme derived by the authors accounted for 98% of the total γ-ray intensity they observed, and from it they calculated the Q-value of the reaction. Finally, the γ-ray intensities were normalized to the Q-value (see Equation 2). Since γ-rays with energies below 1.6 MeV were not measured, lines below 1.6 MeV were taken from Spits1.

Spits1: (1976)

The experiments performed by Spits et al.[13] (designated as Spits1) identified 420 γ-rays from Cl. The experiments were performed at the Petten high-flux reactor at the Reactor Centrum Nederland in Petten, the Netherlands. Polarized as well as unpolarized neutrons were used to aid in the determination of spin and parity assignments of ^{36}Cl energy levels. $PbCl_2$ targets in teflon tubes and a Ge(Li)-NaI pair spectrometer were used to measure the γ-ray spectra. Spectra of contaminants were taken and subtracted from the total measured spectrum, and strong γ-rays from the contaminants were used to calibrate the detectors. Of the 420 γ-rays observed, 236 were placed into a decay scheme which was used to calculate the Q-value of the reaction. The intensities of all γ-rays were then normalized to this Q-value.

Krusche: (1982)

The paper by Krusche et al.[15] identified 400 γ-rays following thermal neutron capture in ^{35}Cl. The source of neutrons was the high flux reactor at the Institut Laue-Langevin in Grenoble, France. The targets were natural KCl, and contributions from contaminants were removed by subtracting their contribution to the capture spectrum. Some contaminant spectra were measured and some were taken from other papers. Krusche is the only author to also explicitly subtract γ-rays from ^{37}Cl. Recall that ^{37}Cl only produces about 0.3% of the total Cl spectrum.

Three curved crystal spectrometers, one Ge(Li) detector, and a Ge(Li)-NaI pair spectrometer measured γ-rays with energies from 0.03 MeV to 10 MeV, the largest energy range of any data source found. The same twelve γ-rays identified by Spits1 but not observed by Kennett were not seen in this experiment, although nine new transitions were observed. All γ-ray energies were calibrated using the 411.8 keV ^{198}Au standard measured by Kessler et al.,[17] and the authors were able to place 326 transitions in the ^{36}Cl decay scheme. They were also able to derive level energies with uncertainties about a factor of 10 smaller than previous studies.

Coceva: (1996)

The experiment by Coceva et al.[14] measured the absolute intensities of γ-rays from the ^{35}Cl(n,γ)^{36}Cl reaction. The experiments were performed at the BR1 Reactor of the SCK, Mol, Belgium, which produced a neutron flux of 10^6 cm^{-2} s^{-1}. The target used to measure the ^{36}Cl γ-rays was C_2Cl_6, and only 24 of the strongest lines were reported. The purpose of the experiment was to establish γ-ray standards based on ^{36}Cl transitions, and much effort was expended to determine the efficiency of the compton-suppressed Ge detector used to measure the spectra. Three sources of γ-rays were used to determine the detector's efficiency; ^{56}Co and ^{24}Na radioactive sources, and γ-rays from a $C_3H_6N_6$ target placed in the neutron beam. Runs totaling 150 hours were performed to determine the detector's efficiency, and the absolute intensity uncertainties of most of the 24 lines reported are less than 3%. No attempt was made to improve the energies of the γ-rays measured; all values of E_γ were taken from Krusche. The authors note that for the 24 lines reported, there is good agreement with the intensities of Spits1 and Krusche, but $\approx$ 7% disagreement with Kennett.

Spits2: (1973)

Finally, the earlier experiments of Spits et al.[9] (designated as Spits2) measured γ-rays from both the ^{37}Cl(n,γ)^{38}Cl and ^{35}Cl(n,γ)^{36}Cl reactions. For both measurements a $PbCl_2$ target enriched to 96.05% ^{37}Cl was used. Despite the high content of ^{37}Cl, capture in ^{35}Cl still contributed 59% of the total spectrum observed. The ^{35}Cl capture spectrum and measurements of contaminant spectra were subtracted to obtain the ^{37}Cl capture spectrum. Two Ge(Li) detectors identified 79 γ-ray transitions in ^{38}Cl. A ^{38}Cl level scheme was determined and the Q-value of the reaction calculated. The measurements were performed at the High Flux Reactor located at the Reactor Centrum Nederland in Petten, the Netherlands. Lines from the ^{35}Cl(n,γ)^{36}Cl reaction were used to calibrate the energies of the ^{37}Cl lines.

The 20 strongest lines from this experiment are listed in Table 4. Also listed are the intensity contributions each line would make to the spectrum of natural Cl. These were calculated by multiplying the intensity of each line by 0.0028, the fractional contribution to the Cl spectrum at incident thermal energies (see Equation 1).

III. Comparison Procedures

The first step in determining the recommended photon production spectrum for Cl focused on 20 of the strongest lines in each data set. The purpose of this first phase of analysis was to determine how well the data sets agreed with each other. To accomplish this, the 20 strongest γ-rays from Lone were identified. The corresponding lines in each of the other data sets (if measured) were then identified, and the data sets were compared on the basis of these matching lines.

Tables 2 and 3 list the matching lines for all of the sets containing data for Cl or ^{35}Cl. Note that some lines were not measured or listed by Orphan, Stelts, Kennett, and ENDF/B-VI. The 20 strongest lines following capture in ^{37}Cl, as well as their contribution to the photon production spectrum of natural Cl, are listed in Table 4. Note that the strongest line from ^{37}Cl contributes only 0.081 photons per 100 captures in Cl. In contrast, the weakest γ-ray from the other data sets is the 5575 keV line from ENDF/B-VI, which contributes ≈ 0.78 photons per 100 captures; nearly a factor of ten larger than the largest contribution from ^{37}Cl. Therefore, data from Spits2 were completely ignored in this first round of analysis.

Table 2: The strongest γ-ray lines for natural Cl and ^{35}Cl. I_γ is number of photons per 100 captures.

Orphan (1970)		Lone (1981)		ENDF/B-VI (1967)		Kennett (1981)	
E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ
1951.3	27.77	1950.93	21.72	—	—	1951.07	20.39
6111.1	20.5	6110.88	20.00	6108.0	25.03	6111.0	20.96
1165.4	14.16	1164.72	19.93	1164.0	11.29	—	—
518.3	14.29	516.73	18.5	520.0	24.53	—	—
788.6	13.46	788.4	15.00	—	—	—	—
1957.5	19.66	1959.13	14.62	1957.0	12.52	1959.2	13.41
7413.8	11.07	7413.8	10.42	7413.0	11.29	7414.17	10.69
—	—	786.26	9.6	—	—	—	—
7790.0	8.61	7790.16	8.55	7498.0	7.77	7790.4	8.69
6620.1	12.99	6619.53	8.01	6620.0	12.95	6619.79	8.31
2864.4	8.8	2863.94	6.93	2870.0	6.04	2863.93	6.63
5715.2	6.0	5715.26	5.5	5707.0	6.04	5715.3	5.68
—	—	6627.64	4.54	—	—	6628.02	4.74
1600.6	5.63	1600.82	4.16	1598.0	2.59	1600.9	3.82
4980.0	4.96	4979.94	4.04	4971.0	4.32	4979.81	3.95
3062.2	4.85	3061.71	3.95	—	—	3061.8	4.01
8578.7	2.99	8578.36	2.91	8577.0	2.59	8578.7	2.84
2676.3	4.25	2675.96	2.58	2681.0	0.86	2676.18	2.06
6977.6	2.23	6977.66	2.26	6979.0	2.59	6978.09	2.4
5516.9	1.95	5517.34	1.73	—	—	5517.38	1.75

Table 3: The strongest γ-ray lines for natural Cl and ^{35}Cl continued. I_γ is number of photons per 100 captures.

Spits1 (1976)		Coceva (1996)		Krusche (1982)		Stelts (1978)	
E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ
1950.99	18.7	1951.1	19.39	1951.145	20.2	—	—
6111.39	19.7	6110.8	20.58	6110.848	20.2	6111.0	19.8
1164.74	25.7	1164.9	27.20	1164.874	27.7	—	—
516.73	22.7	517.1	24.3	517.077	23.4	—	—
788.41	15.0	788.4	16.32	788.432	16.9	—	—
1959.19	12.1	1959.4	12.56	1959.358	12.9	—	—
7414.5	10.0	7414.0	10.52	7413.953	10.4	7414.01	10.2
786.27	9.6	786.3	10.52	786.305	11.2	—	—
7790.96	8.61	7790.3	8.31	7790.325	8.48	7790.4	8.43
6620.07	8.1	6619.6	7.83	6619.638	7.80	6619.76	7.92
2864.06	6.0	2863.8	5.77	2863.815	6.55	—	—
5715.69	5.14	5715.2	5.31	5715.236	5.60	5715.4	5.35
6628.16	4.64	6627.8	4.69	6627.751	4.83	6627.95	4.43
1600.86	3.43	1601.1	3.484	1601.082	3.48	—	—
4980.3	3.53	4979.7	3.616	4979.713	3.60	4979.95	3.62
3061.85	3.5	3061.9	3.521	3061.865	3.88	—	—
8579.31	2.94	8578.6	2.739	8578.59	2.78	8578.65	2.79
2676.0	1.7	2676.3	1.572	2676.300	1.91	—	—
6978.29	2.23	6977.8	2.29	6977.847	2.32	6977.85	2.33
5517.74	1.59	5517.2	1.689	5517.242	1.71	5517.46	1.64

Table 4: The strongest γ-rays for ^{37}Cl.[a] Intensities are number of photons per 100 captures.

E_γ (keV)	Measured $I\gamma$	Contribution to Cl $I\gamma^b$
755.47	29.0	0.081
1692.15	21.1	0.059
4126.9	16.8	0.047
4490.6	15.1	0.042
4415.4	12.8	0.036
671.30	12.4	0.035
308.40	12.1	0.034
637.5	11.5	0.032
1980.93	9.9	0.028
3364.9	8.5	0.024
5352.3	7.6	0.021
862.4	6.7	0.019
1745.35	6.0	0.017
2214.55	5.8	0.016
1225.69	5.4	0.015
363.90	5.0	0.014
4362.1	4.7	0.013
1617.16	4.5	0.013
6108	3.3	0.009
2133.5	2.9	0.008

[a] Measurements are from Spits2.
[b] Contribution to Cl spectrum calculated by multiplying I_γ by 0.0028.

A. Intensity Comparisons

The eight remaining data sets were first compared in pairs. For a given pair of data sets, the intensities of each matching line were examined. For each line, the ratio of the intensities from the two data sets was taken. If the intensities for that line agreed perfectly, the ratio of the two sets was 1.0. The degree of discrepancy between the two data sets *for that particular line* was defined to be the absolute value of their intensity ratio minus 1: $|\frac{I_1}{I_2} - 1|$. This quantity will be called the "intensity difference." The *overall* degree of discrepancy between the two sets was then defined to be the average "intensity difference" of the matching lines. The number of matching lines between data sets ranged from 20 (for example Lone vs. Coceva) down to 10 (for example Stelts vs. Kennett). The average intensity differences between all possible pairs of data sets are listed in Table 5. Note that smaller numbers indicate better agreement between sets.

Table 5 shows the degree to which each data set agrees with any other set. To get a better idea of how well any one data set agreed with *all the others,* the average of the numbers in

Table 5: Average intensity difference between pairs of data sets.

Data Sets Compared	Average Intensity Difference
Orphan / Lone	0.180
Orphan / Stelts	0.175
Orphan / Kennett	0.272
Orphan / Spits1	0.366
Orphan / Coceva	0.378
Orphan / Krusche	0.327
Orphan / ENDF/B-VI	0.541
ENDF/B-VI / Spits1	0.293
ENDF/B-VI / Kennett	0.254
ENDF/B-VI / Stelts	0.154
ENDF/B-VI / Lone	0.364
ENDF/B-VI / Krusche	0.220
ENDF/B-VI / Coceva	0.206
Coceva / Lone	0.125
Coceva / Spits1	0.045
Coceva / Kennett	0.078
Coveva / Krusche	0.039
Coceva / Stelts	0.022
Stelts / Lone	0.035
Stelts / Kennett	0.049
Stelts / Krusche	0.024
Stelts / Spits1	0.031
Spits1 / Lone	0.111
Spits1 / Krusche	0.061
Spits1 / Kennett	0.087
Kennett / Lone	0.054
Kennett / Krusche	0.040
Krusche / Lone	0.095

Table 5 was taken for each set. For example, the average of all values in Table 5 involving comparisons to Kennett was taken. The number obtained is a measure of how well the data from Kennett agrees with the data from all other sets. This quantity will be referred to as the "average intensity disagreement" of a particular data set. The average intensity disagreement for each set is listed in Table 6. Note once again that lower values represent better agreement with the other data sets.

Table 6 shows that data from ENDF/B-VI and Orphan disagree strongly with the majority of the data sets. The average intensity disagreement for most of the sets is between 0.115 and 0.142. The average ENDF/B-VI and Orphan disagreements are more than a factor of two larger. This does not truly show how poor the ENDF/B-VI data is, however. Note from Table 2 that the ENDF/B-VI evaluation does not include *six* of the 20 strongest lines from Lone, including *the strongest line*. Kennett and Stelts also do not include several of the 20 strongest lines from Lone, but that is simply because they did not measure γ-rays with energies below 1.6 MeV and 3.5 MeV, respectively.

The inferiority of ENDF/B-VI and Orphan can be emphasized by removing them from the comparisons. If we repeat the procedure used to generate Table 6, but exclude all ENDF/B-VI and Orphan comparisons, we obtain the values listed in Table 7. Also listed in Table 7 is the percent reduction in intensity disagreement when ENDF/B-VI and Orphan comparisons are removed. The percent reduction in intensity disagreement is defined as

$$percent\ \ reduction \equiv |\frac{old - new}{old}| \cdot 100, \tag{3}$$

where *old* is the intensity disagreement before removing the sets, and *new* is the disagreement after removal. Note that the average intensity disagreement between the remaining sets drops by roughly a factor of two. Clearly most of the intensity disagreement between sets resulted from the presence of Orphan and ENDF/B-VI.

Of the remaining data sets in Table 7, Lone disagrees the most. This is most likely due to the fact that Lone incorporated data from Orphan into its evaluation. Table 8 shows the effect of removing ENDF/B-VI, Orphan, *and* Lone from the comparisons. Note that the level of intensity disagreement drops for most data sets, but the drop is not nearly as strong as when the Orphan and ENDF/B-VI data are excluded. The level of intensity disagreement between the remaining sets is small and roughly constant for sets with all 20 lines.

B. Energy Comparisons

The energies of the matching γ-rays were also compared in a similar manner. Once again, the data sets were first compared in pairs. For each pair of data sets, the absolute value of the energy difference between matching γ-rays was computed: $\Delta E_\gamma^i = |E_\gamma^1 - E_\gamma^2|$, where E_γ^1 is the γ-ray energy from one data set, E_γ^2 is from the other set, and i refers to the i^{th} matching line. The average ΔE_γ was then calculated for each pair of data sets. These were in turn averaged to determine the "average energy disagreement" of each data set. For example, all comparisons to Kennett were averaged to determine how well Kennett's energies agreed with

Table 6: Average of values in Table 5.

Data Set	Average Intensity Disagreement With All Other Sets
Orphan	0.320
Spits1	0.142
Kennett	0.119
Lone	0.138
Stelts	0.070
Coceva	0.128
Krusche	0.115
ENDF/B-VI	0.290

Table 7: Average of values in Table 5, excluding ENDF/B-VI and Orphan.

Data Set	Average Intensity Disagreement With Remaining Sets	Percent Reduction in Disagreement[b]
Spits1	0.067	53%
Kennett	0.062	48%
Lone	0.084	39%
Stelts	0.032	54%
Coceva	0.062	52%
Krusche	0.052	55%

[b]Reduction in disagreement is with respect to the values in Table 6.

Table 8: Average of values in Table 5, excluding ENDF/B-VI, Orphan, and Lone.

Data Set	Average Intensity Disagreement With Remaining Sets	Percent Reduction in Disagreement[b]
Spits	0.056	17%
Kennett	0.064	−5%
Stelts	0.025	38%
Coceva	0.046	25%
Krusche	0.041	18%

[b]Negative values indicate an *increase* in disagreement. Reduction is with respect to the values in Table 7.

the energies of the other sets. This "average energy disagreement" is exactly like the "average intensity disagreement" defined before, except that it measures how well the *energies* of matching lines in one set agree with the *energies* of matching lines in *all other sets.*

The average energy disagreement for each set is listed in Table 9. Since Coceva used the same energies measured by Krusche, comparisons with Coceva were eliminated since they would in effect be weighting the Krusche energy values twice. Note again that smaller values indicate better agreement with the other sets.

Once again we find extreme disagreement between ENDF/B-VI and all other sets of data. If we exclude the ENDF/B-VI data from the comparisons we obtain the average energy disagreements listed in Table 10. As before, the average energy disagreement drops dramatically when the ENDF/B-VI data is excluded. Of the remaining sets, Orphan and Spits1 disagree nearly twice as much as the other data sets. If they are excluded the level of disagreement again drops, and becomes very uniform, as shown in Table 11. It is interesting to note that, unlike in the intensity comparisons, Lone does not disagree much more than the other data sets. This is due to the fact that the energies quoted by Lone are *weighted averages* of the energies of Orphan, Spits1, and Stelts, whereas its intensities are unweighted averages.

C. Conclusions of Preliminary Analysis

Based on these simple comparisons the following conclusions have been drawn. First, the data in ENDF/B-VI and Orphan are unusable. The energies and intensities of their γ-rays disagree strongly with every other source of recent photon production data. Furthermore, they are both missing a great number of lines, with ENDF/B-VI missing some of the strongest lines but including other weaker ones. Second, while the compilation by Lone is much improved over Orphan, it probably should not be used as well. It includes data from Orphan, which is very low-quality, and also includes about 20 weak transitions not confirmed by recent experiments (Kennett and Krusche).

These conclusions eliminate the use of ENDF/B-VI, Orphan and Lone in determining a recommended photon production spectrum for Cl. Therefore, the six experimental papers Spits1, Spits2, Kennett, Stelts, Coceva, and Krusche have been analyzed line by line to generate a recommended photon production spectrum for Cl. Data from Spits2 were simply weighted and inserted into the evaluation. Since ^{37}Cl contributes so little ($< 0.3\%$) to the photon production of Cl, no older sources of ^{37}Cl(n,γ)^{38}Cl data were sought for evaluation. The other five papers contain photon production data for Cl or ^{35}Cl and were carefully compared in generating this evaluation.

D. Final Evaluation Procedure

In comparing the five remaining data sets, Krusche and Coceva were weighted heavily in deciding the energy and intensity of each line. This decision is based on several facts. First, Krusche (1982) and Coceva (1996) represent the latest experimental data that could be found. Second, the energy level uncertainties determined by Krusche are roughly a factor of

Table 9: Average energy disagreement of each set.

Data Set	Average Energy Disagreement With All Other Sets (keV)
Orphan	4.31
Spits1	4.35
Kennett	4.79
Lone	4.22
Stelts	6.77
Krusche	4.20
ENDF/B-VI	27.22

Table 10: Average energy disagreement of each set with ENDF/B-VI excluded.

Data Set	Average Energy Disagreement With Remaining Sets (keV)
Orphan	0.41
Spits1	0.38
Kennett	0.21
Lone	0.26
Stelts	0.21
Krusche	0.24

Table 11: Average energy disagreement of each set with ENDF/B-VI, Orphan, and Spits1 excluded.

Data Set	Average Energy Disagreement With Remaining Sets (keV)
Kennett	0.14
Lone	0.18
Stelts	0.13
Krusche	0.14

ten smaller than the uncertainties determined by all other authors. Coceva did not even try to improve on Krusche's energy measurements, and simply lists Krusche's energies in his paper. Third, the purpose of Coceva's paper was to establish an intensity standard based on transitions in Cl, and it seems that the efficiency and energy calibrations performed by Coceva were very accurate and precise. Coceva is also the only author to use compton-suppressed Ge detectors. For these reasons, the energies and intensities of the 24 lines listed by Coceva were used in the present evaluation.

To determine the energies and intensities of the remaining lines, a two-step procedure was used. First, γ-rays considered to match lines measured by Krusche were identified in each set. Lines from other data sets were considered a match if their energies and intensities agreed closely with Krusche. Since energy measurements are usually much more precise than intensity measurements, closely matching energies were considered a stronger indication of a match than closely matching intensities. For each matching line, the energies and intensities from each data set were then compared, and the values of E_γ and I_γ adopted were decided separately. The values from Krusche were used unless at least two other experimenters observed the γ-ray *and* the other experimenters' values agreed with each other, but disagreed substantially with Krusche. For the 12 such cases observed, a simple average of the other values was adopted for E_γ and/or I_γ. A simple average was used because all such cases included data from Kennett, for which energy and intensity uncertainties were not listed.

In the second step, lines not matching lines measured by Krusche were examined. Lines that only Krusche observed were included in the recommended spectrum. This decision is based on the assumed superiority of Krusche's measurements, as well as the fact that Krusche measured a much larger range of γ-ray energies than any other author. Lines observed by other experimenters but not Krusche were included if at least two other experimenters observed the line, and the experimenters' values were in decent agreement. In such cases a simple average of E_γ and/or I_γ was adopted for the line. Only 13 such lines were added.

IV. Recommended Photon Production Spectrum for Cl

Once the final spectrum was obtained, the total radiated energy per single neutron capture was calculated using Equation 2 and found to be 8.537299 MeV. Using the $^{35}\mathrm{Cl}(\mathrm{n},\gamma)^{36}\mathrm{Cl}$ Q-value of Krusche and the $^{37}\mathrm{Cl}(\mathrm{n},\gamma)^{38}\mathrm{Cl}$ Q-value of Spits2, the abundance and cross-section weighted Q-value for the Cl(n,γ) reaction was determined to be 8.572759 MeV. Thus 99.6% of the total yield, based on these Q-values, is accounted for in the unnormalized spectrum.

The recommended photon production spectrum at incident thermal energies for Cl is listed in Table 12. The γ-ray intensities have been multiplied by 1.004153 to ensure that the total yield per capture equals 8.572759 MeV, the abundance and cross-section weighted Q-value. The source or combination of sources for each of the 482 γ-rays is also listed in Table 12.

Table 12: Recommended photon production spectrum at incident thermal neutron energies for natural Cl. Intensities are number of photons per 100 captures, and have been normalized to give a total yield per capture of 8572.76 keV.

Eγ keV	Iγ	Source(s):	Eγ keV	Iγ	Source(s):
85.743	0.0076	Krusche	441.000	0.0271	Krusche
89.838	0.0030	Krusche	444.490	0.0331	Krusche
90.028	0.0020	Krusche	447.848	0.0070	Krusche
108.740	0.0040	Krusche	455.670	0.0141	Krusche
111.546	0.0050	Krusche	455.968	0.0070	Krusche
115.424	0.0030	Krusche	459.570	0.0297	Krusche
133.558	0.0070	Krusche	462.253	0.0171	Krusche
137.195	0.0030	Krusche	463.699	0.0064	Krusche
151.159	0.0030	Krusche	465.270	0.0131	Krusche
204.373	0.0119	Krusche	466.060	0.0164	Krusche
212.726	0.0090	Krusche	466.625	0.0331	Krusche
225.526	0.0054	Krusche	468.359	0.0894	Krusche
225.871	0.0037	Krusche	468.765	0.0099	Krusche
236.710	0.0059	Krusche	478.690	0.0884	Krusche
241.334	0.0040	Krusche	485.868	0.0100	Krusche
272.760	0.0070	Krusche	495.891	0.0095	Krusche
279.435	0.0090	Krusche	502.309	0.0179	Krusche
288.600	0.0067	Spits2	503.985	0.0158	Krusche
292.178	0.2641	Krusche	508.866	0.3515	Krusche
302.751	0.0068	Krusche	517.077	24.4009	Coceva
308.400	0.0340	Spits2	532.906	0.1105	Krusche
308.722	0.0372	Krusche	537.667	0.0087	Krusche
337.617	0.0588	Krusche	539.600	0.0371	Krusche
340.270	0.0050	Krusche	554.000	0.0076	Spits2
342.311	0.0176	Krusche	576.417	0.0042	Krusche
343.038	0.0080	Krusche	582.324	0.0102	Krusche
358.288	0.2209	Krusche	590.495	0.0040	Krusche
363.900	0.0141	Spits2	595.840	0.0040	Krusche
369.281	0.0623	Krusche	602.839	0.0040	Krusche
371.562	0.0044	Krusche	616.152	0.0864	Krusche
376.425	0.0041	Krusche	619.040	0.0059	Krusche
422.060	0.0040	Krusche	622.940	0.0060	Krusche
427.534	0.0131	Krusche	628.941	0.0090	Krusche
427.855	0.0320	Krusche	630.556	0.0106	Krusche
428.239	0.0128	Krusche	632.438	0.3203	Krusche
435.969	0.1647	Krusche	637.500	0.0323	Spits2
436.222	1.0544	Krusche	640.330	0.0157	Krusche

Table 12: Recommended photon production spectrum at incident thermal neutron energies for natural Cl continued. Intensities are number of photons per 100 captures, and have been normalized to give a total yield per capture of 8572.76 keV.

Eγ keV	Iγ	Source(s):	Eγ keV	Iγ	Source(s):
656.000	0.0068	Krusche	945.900	0.0022	Spits2
659.653	0.0131	Krusche	946.297	0.0241	Krusche
661.707	0.0211	Krusche	958.210	0.0056	Spits2
663.429	0.0050	Krusche	958.559	0.0572	Krusche
665.636	0.0733	Krusche	968.173	0.0318	Krusche
671.300	0.0349	Spits2	975.740	0.0173	Krusche
696.499	0.0142	Krusche	979.615	0.0338	Krusche
703.204	0.1145	Krusche	989.634	0.0412	Krusche
712.107	0.0050	Krusche	998.801	0.0335	Krusche
717.025	0.0171	Krusche	1020.497	0.0733	Krusche
723.105	0.0161	Krusche	1029.600	0.0062	Spits2
723.200	0.0014	Spits2	1034.261	0.3243	Krusche
727.999	0.0221	Krusche	1035.125	0.1235	Krusche
729.106	0.0064	Krusche	1035.892	0.0592	Krusche
735.578	0.0365	Krusche	1043.473	0.0994	Krusche
755.470	0.0815	Spits2	1066.723	0.0884	Krusche
760.365	0.0239	Krusche	1068.720	0.0392	Krusche
780.660	0.0120	Krusche	1076.723	0.0318	Krusche
786.305	10.5637	Coceva	1086.662	0.0693	Krusche
788.432	16.3878	Coceva	1089.430	0.0332	Krusche
812.608	0.0683	Krusche	1095.720	0.0171	Krusche
832.080	0.1004	Krusche	1125.700	0.0031	Spits2
841.901	0.0386	Krusche	1127.810	0.0382	Krusche
848.449	0.0301	Krusche	1131.247	1.9189	Coceva
859.420	0.1064	Krusche	1162.785	2.2995	Krusche
862.400	0.0188	Spits2	1164.874	27.3130	Coceva
864.021	0.1225	Krusche	1170.922	0.5121	Krusche
865.395	0.0201	Krusche	1201.980	0.1165	Krusche
870.484	0.0157	Krusche	1225.700	0.0152	Spits2
884.870	0.0191	Krusche	1230.846	0.1014	Krusche
886.795	0.0171	Krusche	1258.028	0.0602	Krusche
898.175	0.0191	Krusche	1264.600	0.0673	Krusche
904.508	0.0471	Krusche	1265.420	0.0833	Krusche
912.881	0.0964	Krusche	1273.100	0.0020	Spits2
936.800	0.0048	Spits2	1308.800	0.0028	Spits2
936.921	0.5914	Krusche	1327.418	1.2753	Krusche
945.131	0.1396	Krusche	1372.855	0.3856	Krusche

Table 12: Recommended photon production spectrum at incident thermal neutron energies for natural Cl continued. Intensities are number of photons per 100 captures, and have been normalized to give a total yield per capture of 8572.76 keV.

Eγ keV	Iγ	Source(s):	Eγ keV	Iγ	Source(s):
1381.980	0.0415	Krusche	1869.600	0.0014	Spits2
1425.430	0.0713	Krusche	1912.300	0.0028	Spits2
1434.010	0.0073	Spits2	1936.961	0.4318	Krusche
1469.500	0.0014	Spits2	1937.000	0.0022	Spits2
1496.702	0.1717	Krusche	1941.700	0.0020	Spits2
1510.750	0.1506	Krusche	1951.145	19.4705	Coceva
1515.626	0.0773	Krusche	1959.358	12.6122	Coceva
1517.056	0.0773	Krusche	1971.900	0.0008	Spits2
1524.990	0.0803	Krusche	1975.610	0.6969	Krusche
1526.260	0.1336	Krusche	1980.930	0.0278	Spits2
1528.610	0.1215	Krusche	1987.600	0.0020	Spits2
1601.082	3.4985	Coceva	1992.900	0.0045	Spits2
1605.990	0.0613	Krusche	1996.330	0.2430	Krusche
1617.160	0.0127	Spits2	2003.446	0.2038	Krusche
1623.320	0.1054	Krusche	2011.760	0.1165	Krusche
1626.985	0.2992	Krusche	2022.098	0.5202	Krusche
1640.116	0.4288	Krusche	2030.100	0.0014	Spits2
1648.305	0.5262	Krusche	2034.600	0.0028	Spits2
1654.320	0.0045	Spits2	2034.634	0.7511	Krusche
1657.254	0.2370	Krusche	2041.150	0.5121	Spits1, Kennett
1679.761	0.2018	Krusche	2075.547	0.7933	Spits1, Kennett
1683.808	0.2259	Krusche	2091.819	0.2069	Krusche
1692.150	0.0593	Spits2	2092.300	0.0011	Spits2
1701.000	0.0014	Spits2	2096.300	0.0051	Spits2
1709.830	0.2099	Krusche	2110.247	0.2028	Krusche
1729.935	0.3454	Krusche	2133.220	0.0593	Krusche
1731.155	0.2199	Krusche	2133.500	0.0082	Spits2
1743.148	0.2500	Krusche	2156.213	0.6818	Krusche
1745.350	0.0169	Spits2	2179.529	0.2671	Krusche
1786.180	0.2179	Krusche	2200.118	0.3926	Krusche
1788.059	0.3756	Krusche	2201.100	0.0011	Spits2
1806.421	0.1597	Krusche	2205.200	0.0034	Spits2
1818.700	0.0006	Spits2	2214.550	0.0163	Spits2
1820.800	0.0025	Spits2	2224.684	0.1657	Krusche
1828.501	0.3695	Krusche	2229.966	0.0618	Krusche
1847.575	0.1707	Spits1, Kennett	2231.312	0.3494	Krusche
1858.089	0.2902	Krusche	2235.363	0.1908	Krusche

Table 12: Recommended photon production spectrum at incident thermal neutron energies for natural Cl continued. Intensities are number of photons per 100 captures, and have been normalized to give a total yield per capture of 8572.76 keV.

Eγ keV	Iγ	Source(s):	Eγ keV	Iγ	Source(s):
2239.713	0.2430	Krusche	2588.415	0.1456	Spits1, Kennett
2245.200	0.0034	Spits2	2592.465	0.1757	Spits1, Kennett
2246.213	0.1948	Krusche	2622.880	0.6356	Krusche
2248.900	0.0003	Spits2	2639.057	0.1556	Krusche
2254.258	0.2380	Krusche	2647.600	0.2792	Krusche
2265.790	0.0627	Krusche	2653.490	0.0723	Krusche
2276.400	0.0014	Spits2	2662.910	0.1115	Krusche
2282.861	0.1406	Krusche	2676.300	1.5785	Coceva
2285.700	0.0065	Spits2	2682.398	0.1587	Krusche
2289.887	0.3213	Spits1, Kennett	2698.620	0.0569	Krusche
2290.000	0.0014	Spits2	2705.400	0.0039	Spits2
2311.406	1.0945	Krusche	2711.618	0.1205	Spits1, Kennett
2326.025	0.2350	Krusche	2727.887	0.1356	Krusche
2342.270	0.0419	Krusche	2733.600	0.0003	Spits2
2351.500	0.0031	Spits2	2740.620	0.1275	Krusche
2355.890	0.1175	Krusche	2743.200	0.0042	Spits2
2364.650	0.0587	Krusche	2753.010	0.1115	Krusche
2382.710	0.1496	Krusche	2797.986	0.2952	Krusche
2394.636	0.1566	Krusche	2800.846	0.6025	Spits1, Kennett
2407.284	0.1958	Krusche	2811.011	0.4840	Krusche
2418.553	0.5533	Krusche	2813.600	0.0025	Spits2
2422.900	0.0053	Spits2	2831.000	0.0006	Spits2
2429.540	0.1667	Krusche	2845.498	1.2753	Krusche
2467.720	0.2882	Krusche	2863.815	5.7940	Coceva
2469.879	0.7340	Krusche	2867.160	0.6176	Krusche
2489.850	0.4569	Krusche	2871.407	0.3123	Krusche
2494.831	0.2079	Krusche	2876.640	0.5653	Krusche
2495.945	0.2310	Spits1, Kennett	2896.232	0.5553	Krusche
2524.670	0.1105	Krusche	2941.331	0.1295	Krusche
2527.944	0.2470	Krusche	2953.230	0.0638	Krusche
2537.255	0.4388	Krusche	2855.000	0.0037	Spits2
2544.400	0.0011	Spits2	2895.200	0.0048	Spits2
2549.810	0.2922	Krusche	2955.120	0.0720	Krusche
2556.585	0.1205	Spits1, Kennett	2975.235	1.0503	Coceva
2567.462	0.1727	Krusche	2994.707	0.9138	Krusche
2569.000	0.0011	Spits2	3001.067	0.6999	Krusche
2569.880	0.0703	Krusche	3015.985	1.1357	Krusche

Table 12: Recommended photon production spectrum at incident thermal neutron energies for natural Cl continued. Intensities are number of photons per 100 captures, and have been normalized to give a total yield per capture of 8572.76 keV.

Eγ keV	Iγ	Source(s):	Eγ keV	Iγ	Source(s):
3025.240	0.0596	Krusche	3504.166	0.1998	Krusche
3040.230	0.0444	Krusche	3512.210	0.0775	Krusche
3051.000	0.0022	Spits2	3526.850	0.0751	Krusche
3061.865	3.5356	Coceva	3538.400	0.0042	Spits2
3067.840	0.1767	Krusche	3558.230	0.1727	Krusche
3086.280	0.0884	Krusche	3561.258	0.6959	Krusche
3105.760	0.1697	Krusche	3566.400	0.0025	Spits2
3116.216	0.9981	Krusche	3566.611	0.3113	Krusche
3135.330	0.1163	Krusche	3581.900	0.1336	Krusche
3138.000	0.0065	Spits2	3589.234	0.6075	Krusche
3151.790	0.0585	Krusche	3599.251	0.5412	Krusche
3159.680	0.0703	Spits1, Kennett	3604.112	0.4027	Krusche
3197.590	0.0904	Spits1, Kennett	3612.620	0.1095	Krusche
3202.100	0.0014	Spits2	3621.670	0.1175	Krusche
3203.790	0.0753	Krusche	3627.270	0.1275	Krusche
3210.590	0.0586	Krusche	3634.480	0.2979	Spits1, Kennett, Stelts
3213.100	0.0028	Spits2	3635.300	0.0045	Spits2
3244.360	0.0992	Krusche	3645.580	0.0406	Krusche
3250.357	0.2561	Krusche	3660.230	0.2099	Krusche
3255.700	0.0372	Krusche	3683.900	0.0059	Spits2
3271.480	0.1009	Krusche	3707.824	0.1828	Krusche
3291.880	0.0944	Krusche	3728.000	0.0440	Krusche
3295.850	0.0924	Krusche	3736.541	0.1978	Krusche
3311.710	0.0437	Krusche	3743.770	0.0962	Krusche
3316.363	0.2581	Krusche	3749.905	0.3103	Krusche
3333.090	0.8304	Krusche	3774.857	0.2644	Spits1, Kennett, Stelts
3349.747	0.2390	Krusche	3809.630	0.0510	Krusche
3364.900	0.0239	Spits2	3821.581	1.0995	Krusche
3374.895	0.6025	Krusche	3825.530	0.8455	Krusche
3385.530	0.0423	Krusche	3860.180	0.1074	Krusche
3428.863	0.8987	Krusche	3893.000	0.0039	Spits2
3435.890	0.1346	Krusche	3916.370	0.0688	Krusche
3457.440	0.0514	Krusche	3962.600	0.4084	Spits1, Kennett, Stelts
3458.400	0.0329	Krusche	3974.700	0.0056	Spits2
3470.060	0.1007	Krusche	3977.240	0.1265	Krusche
3489.730	0.0118	Krusche	3981.064	1.0323	Krusche
3500.378	0.3314	Krusche	3997.140	0.0690	Krusche

Table 12: Recommended photon production spectrum at incident thermal neutron energies for natural Cl continued. Intensities are number of photons per 100 captures, and have been normalized to give a total yield per capture of 8572.76 keV.

Eγ keV	Iγ	Source(s):	Eγ keV	Iγ	Source(s):
4003.265	0.0904	Spits1, Kennett	4547.473	0.4549	Krusche
4028.054	0.1938	Krusche	4551.410	0.1315	Krusche
4041.080	0.0849	Krusche	4558.080	0.0151	Krusche
4054.226	0.6286	Krusche	4583.815	0.0703	Spits1, Kennett
4061.048	0.2430	Krusche	4586.602	0.2731	Krusche
4082.664	0.7883	Krusche	4591.850	0.0482	Krusche
4086.620	0.0633	Krusche	4597.500	0.0485	Krusche
4091.500	0.0303	Krusche	4616.436	0.6848	Krusche
4097.900	0.0286	Krusche	4637.590	0.0140	Krusche
4111.760	0.1007	Krusche	4652.900	0.0298	Krusche
4126.900	0.0472	Spits2	4683.510	0.0582	Krusche
4138.456	0.3046	Spits1, Kennett, Stelts	4728.966	0.7049	Krusche
4148.600	0.0110	Krusche	4735.100	0.0025	Spits2
4164.170	0.0770	Krusche	4747.140	0.0361	Krusche
4165.500	0.0028	Spits2	4753.310	0.1240	Krusche
4169.200	0.0578	Krusche	4757.480	0.1371	Krusche
4173.790	0.0206	Krusche	4791.440	0.0281	Krusche
4192.300	0.0271	Krusche	4815.297	0.1548	Krusche
4205.140	0.1237	Krusche	4817.415	0.0653	Spits1, Kennett
4264.010	0.0308	Krusche	4829.064	0.1948	Krusche
4294.580	0.0426	Krusche	4884.850	0.0932	Krusche
4298.384	0.3906	Krusche	4944.335	1.1116	Krusche
4308.280	0.0429	Krusche	4945.195	0.6376	Krusche
4355.000	0.1465	Krusche	4950.850	0.1597	Krusche
4362.100	0.0132	Spits2	4979.713	3.6310	Coceva
4405.400	0.0028	Spits2	4989.960	0.3103	Krusche
4413.590	0.1757	Krusche	5000.550	0.0461	Krusche
4415.400	0.0360	Spits2	5017.726	0.4669	Krusche
4416.110	0.1225	Krusche	5078.818	0.1526	Krusche
4420.600	0.0365	Krusche	5088.050	0.0379	Krusche
4422.700	0.0062	Spits2	5109.250	0.0870	Krusche
4440.399	1.0513	Coceva	5122.820	0.0347	Krusche
4458.200	0.1062	Krusche	5142.120	0.1004	Spits1, Kennett
4473.330	0.0271	Krusche	5150.195	0.2028	Krusche
4490.600	0.0425	Spits2	5204.230	0.2059	Krusche
4518.120	0.1556	Krusche	5246.189	0.2711	Krusche
4524.866	0.4609	Krusche	5246.909	0.2711	Krusche

Table 12: Recommended photon production spectrum at incident thermal neutron energies for natural Cl continued. Intensities are number of photons per 100 captures, and have been normalized to give a total yield per capture of 8572.76 keV.

Eγ keV	Iγ	Source(s):
5262.760	0.0989	Krusche
5352.300	0.0214	Spits2
5372.350	0.0496	Krusche
5473.340	0.0861	Krusche
5517.202	1.6960	Coceva
5584.617	0.5382	Krusche
5603.867	0.3595	Krusche
5634.380	0.0572	Krusche
5702.630	0.4328	Krusche
5715.187	5.3321	Coceva
5733.480	0.5121	Krusche
5756.520	0.0803	Spits1, Kennett
5777.450	0.1677	Spits1, Kennett, Stelts
5902.700	1.1086	Coceva
5956.294	0.1918	Krusche
6051.160	0.0422	Krusche
6086.744	0.8475	Krusche
6108.000	0.0093	Spits2
6110.848	20.6655	Coceva
6185.190	0.1235	Spits1, Kennett, Stelts
6252.990	0.0751	Krusche
6267.810	0.4428	Krusche
6339.720	0.0729	Krusche
6343.880	0.0599	Krusche
6378.945	0.1998	Krusche
6422.845	0.2792	Krusche
6487.040	0.1379	Krusche
6544.112	0.1541	Krusche
6619.638	7.8625	Coceva
6627.751	4.7095	Coceva
6641.980	0.1868	Krusche
6951.807	0.1585	Krusche
6977.847	2.2995	Coceva
7377.380	0.0311	Krusche
7413.953	10.5637	Coceva
7558.210	0.0231	Krusche
7790.325	8.3445	Coceva
8578.590	2.7504	Coceva

V. Summary

This research note presents a recommended photon production spectrum at incident thermal energies for natural Cl. The recommended spectrum was generated by analyzing nine sets of photon production data. Six of the nine data sets represent the most recent experimental data that could be found, with the other three being compilations still in use. The analysis revealed that the two older compilations, ENDF/B-VI[10] and Orphan[4], are of extremely low-quality. Data from Lone[8], the only other compilation, are of much higher-quality but still not adequate for some applications. The remaining six sets (all recent experimental papers) are of extremely high quality, and are in excellent agreement.

The recommended spectrum for Cl was based on these six experimental papers. The γ-ray energies and intensities from the most recent measurements (Coceva[14] and Krusche[15]) were adopted most frequently. Coceva's 24 measured γ-rays were in excellent agreement with all other authors, and were adopted since they represented the most recent experimental data. The remaining lines in the recommended spectrum were taken from Krusche unless there were serious disagreements with other authors. For example, measurements from other authors were adopted if they agreed with each other, but disagreed substantially with Krusche. In such cases a simple average of the other authors' E_γ and/or I_γ was taken. Lines observed by Krusche but not other authors were included since Krusche's measurements covered the broadest γ-ray energy range, and appeared to be of higher quality. Lines observed by other authors but not by Krusche were included if at least two other experimenters observed the line, and were in decent agreement. In such cases a simple average of the other authors' E_γ and/or I_γ was taken. The intensities of γ-rays produced by thermal-neutron capture in an isotope of Cl were multiplied by the isotopes' fractional contribution to the total Cl photon spectrum (see Equation 1).

The resulting recommended γ-ray spectrum is listed in Table 12. The intensities have been normalized to give a total energy yield per neutron capture of 8572.76 keV. This is the abundance and cross-section weighted Q-value of the Cl(n,γ) reaction as measured by Krusche and Spits2.[9] Before normalization, the total yield was 99.6% of this Q-value.

The next task associated with ACTI is to assess the quality of photon production data for natural Chromium. As we have seen in the assessment of photon production data for Cl, experimental papers may be far superior to commonly used compilations. Therefore, the assessment of photon production data for Cr will involve comparisons of ENDF, the most recent work based on ENSDF data, and experimental data.

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